Modeling transpiration with sun-induced chlorophyll fluorescence via water use efficiency and stomatal conductance

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Key Points:

- Transpiration can be modeled accurately by SIF observations via water use efficiency and stomatal conductance methods.
- Mechanism models outperformed the linear models for monitoring transpiration.
- Air dryness has an important impact on the relationship between transpiration and SIF.

Abstract

Successfully applied in the carbon research area, sun-induced chlorophyll fluorescence (SIF) has raised the interest of researchers from the water research domain. However, the mechanism between SIF emitted by plants and transpiration (T) has not been fully explored. To improve the understanding of the relationship between SIF and T, we developed two SIF-T models, namely the WUE model and conductance model, based on carbon-water coupling framework. Hourly data observation at 4 sites were used to develop and validate the model, which were covered C3 and C4 plants. Compared with traditional model, results show that the developed WUE model and conductance model have higher R^2 and lower RMSE. The developed models further indicate the potential and mechanism in estimating water flux by remotely sensed SIF observations.

1 Introduction

Evapotranspiration (ET) is not only a pipeline of the water cycle in the air but also an important influence factor of energy balance as a carrier of latent heat. Previous works indicated transpiration (T) occupies a dominant position in evapotranspiration [*Good et al.*, 2015; *Jasechko et al.*, 2013].

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In some ecosystems, T could reach 95% of the total ET [*Stoy et al.*, 2019]. T is also closely coupled with the carbon plant productivity [*Kool et al.*, 2014]. Therefore, an accurate understanding of the spatiotemporal changes of T is crucial for understanding the substance and energy interactions between the land surface and the atmosphere.

In this century, Sun-induced chlorophyll fluorescence (SIF) renewed the gross primary production (GPP) estimation from ground to space [*Frankenberg and Berry*, 2018; *Ryu et al.*, 2019; *Schimel et al.*, 2019]. Considering the connection between photosynthesis and transpiration, SIF may serve as a pertinent constrain estimates for transpiration. [*Alemohammad et al.*, 2017; *Jonard et al.*, 2020]. Recently, Empirical analysis based on ground and remote sensing SIF observation showed SIF is strongly related to T, [*Lu et al.*, 2018] reconstructed the full band SIF and exploit the capacity of individual SIF bands and their combinations for deriving T with empirical linear regression and Gaussian Process Regression model at Harvard Forest. [*Pagán et al.*, 2019] used radiation corrected GOME-2 SIF observations to diagnose transpiration efficiency understood as the ratio between transpiration and potential evaporation worldwide. [*Maes et al.*, 2020] investigated the empirical link between SIF and T using satellite SIF (GOME-2 and OCO-2) and SCOPE model at sites from FLUXNET. However, the studies mentioned above relate T with SIF empirically, not mechanistically. SIF is the light signal from the excited chlorophyll a molecules after absorption of photosynthetically active radiation. The information about the electron transport (J) from photosystem II to photosystem I contained in SIF makes the signal a powerful tool to predict GPP [*Gu et al.*, 2019; *Köhler et al.*, 2018; *Zhang et al.*, 2014]. Furthermore, the essential of understanding the SIF-T relationship should lie in the coupling between the carbon and water cycles.

The carbon and water cycles between the biosphere and atmosphere are strongly coupled [*Gentine et al.*, 2019]. The trade-off between photosynthesis and water vapor loss is arguably the most central constraint on plant function [*Wolz et al.*, 2017]. Water-use efficiency (WUE) and stomatal conductance (gs, or canopy conductance, gc) are two key metrics of carbon - water coupling. WUE is defined as the amount of carbon assimilated relative to water use [*Leakey et al.*, 2019]. [*Maes et al.*, 2020] reported WUE and related variables show a most important impact on the SIF-T relation. Plants take in carbon dioxide and breath out water through stomata simultaneously. Stomata played a key role in the carbon-water coupling, even the whole Earth System [*Berry et al.*, 2010]. By analyzing the empirical link of SIF and canopy conductance, [*Shan et al.*, 2019] reported the empirically linear linkage between gs and SIF data from C3 forest, cropland, and grassland ecosystems, and T calculated by SIF-based conductance agreed well with ET observed by flux towers.

Even though some studies have been conducted for T estimation based on SIF observations, they usually use the empirical method. It is unclear how can WUE and gs be used to model T by SIF mechanistically. In this paper, two carbon-water coupling indicators: water use efficient and stomatal conductance are introduced to clarify the physical relevance between SIF and T. Using the concept of these two indicators, two mechanism SIF-T models are built and tested based on hourly ground observations at four sites, including two C4 and two C3 sites. The results are expected to improve our understanding of the link between SIF and T.

2 Materials and Methods

2.1 Materials

SIF and corresponding observation (eg. meteorological variables, flux observation, and vegetation indexes) are acquired at four sites including two maize field sites (Daman from Heihe river basin, China, DM; Huailai from Haihe river basin, China, HL), one temperate deciduous forest site (Harvard Forest from AmeriFlux network, US, HF), and a subalpine conifer forest (Niwot Ridge from AmeriFlux network, US, NR). The characteristics of these sites are summarized in Table 1. The SIF measurements of DM and HL sites (760 nm) were conducted using a tower-based automatic measurement system named "SIFSpec" [*Du et al.*, 2018] and retrieved using the 3FLD method [*Liu et al.*, 2020]. The SIF data (745- to 758-nm) of NR were from a scanning spectrometer (PhotoSpec) on the top of the 26 meters tower. SIF data in winter were abandoned in this study because the subalpine trees at the NR site undergone significant physiological stress during the cold climate [*Magney et al.*, 2019]. The SIF data of HF were retrieved from FluoSpec deployed about 5 m above the canopy on the top of a tower and extracted by spectral fitting methods at 760 nm [*Yang et al.*, 2015].

Meteorological variables include net radiation (Rn), relative humidity and so on (See Table 2). Latent heat (LE) and net ecosystem exchange (NEE) are taken from flux observed by Eddy Covariance towers. Gross primary production (GPP) was separated from net ecosystem exchange (NEE) following [*Reichstein et al.*, 2005] and [*Lasslop et al.*, 2010] via the REddyProcWeb online tool (https://www.bgcjena.mpg.de/bgi/index.php/Services /REddyProcWeb). Leaf area index (LAI) of all four sites was acquired from the MCD15A3H dataset with 4-day and 500 m temporal-spatial resolution [*Myneni et al.*, 2015] and interpolated to hourly scale on Google Earth Engine [*Gorelick et al.*, 2017]. One hour before the rainfall and six hours after the rainfall data were excluded to minimize the influence of canopy interception.

T modeled by SIF is evaluated by T_{Zhou} partitioned from ET. [*Zhou et al.*, 2014] proposed an index called underlying water-use efficiency (uWUE) by combining the optimal stomatal behavior model with Fick's law. This method was developed based on flux tower data of 14 sites, including the HF site, and successfully applied to Heihe River Basin [*Zhou et al.*, 2018], including the DM site. Especially, at the DM site, T/ET estimated by the uWUE method agreed with the isotope method well during the peak growing season [*Bai et al.*, 2019].

2.2 WUE Model

SIF and GPP can both be represented in the form of light use efficiency (LUE) model:

$$\mathrm{SIF} = \mathrm{APAR}\ \Phi_{\mathrm{F}}\ \Omega_{\mathrm{c}} \tag{1}$$

$$\mathrm{GPP} = \mathrm{APAR\ LUE} \tag{2}$$

where APAR stands the photosynthetically active radiation absorbed by photosynthetic pigments, Φ_{F} is the fluorescence quantum yield, and Ω_c is the probability of SIF photon escaping from the canopy. Combining Eqn 1 with Eqn 2, we can obtain a linear model between SIF and GPP:

$$\mathrm{GPP} = \mathrm{SIF}\frac{\mathrm{LUE}}{\Phi_{\mathrm{F}}\ \Omega_{\mathrm{c}}} \tag{3}$$

where LUE is the light-use-efficiency. Based on previous works [*Guanter et al.*, 2014; *Li et al.*, 2018; *Sun et al.*, 2017; *Liu et al.*, 2017; *Magney et al.*, 2019; *Yang et al.*, 2015], the factor $\frac{\mathrm{LUE}}{\Phi_{\mathrm{F}}\times\Omega_{\mathrm{c}}}$ can be set as a constant for a specific plant type, and GPP can be calculated by SIF directly. For C3 and C4 plants, WUE is relatively stable. Many works derived T from GPP by treating WUE as a constant value during certain period [*Scott and Biederman*, 2017; *Yang et al.*, 2015]. Under this assumption T can be calculated by SIF via the following equation:

$$\mathrm{GPP_{linear}} = \mathrm{k1\ SIF} \tag{4}$$

$$\mathrm{T_{linear}} = \mathrm{k2\ GPP_{linear}} \tag{5}$$

where k1, k2 are two parameters denoting $\frac{\mathrm{LUE}}{\Phi_{\mathrm{F}}\times\Omega_{\mathrm{c}}}$ and WUE respectively. Eqn 5 is the theory base of the empirical linear relationship between SIF and T.

However, WUE is strongly affected by the dryness of air from leaf to ecosystem scale. The relationship between GPP and T improved significantly by incorporating the effects of the vapor pressure deficit (VPD) from diurnal to annual time scales [*Beer et al.*, 2009; *Zhou et al.*, 2014]. Moreover, [*Jonard et al.*, 2020] pointed out the atmospheric demand for water helps explaining a lot variability in the SIF–T relationship at the ecosystem scale. Here we proposed a WUE model:

$$\mathrm{GPP_{WUE}} = \mathrm{k3\ SIF} \tag{6}$$

$$\mathrm{T_{WUE}} = \mathrm{k4\ VPD^{k5}\ GPP_{WUE}} \tag{7}$$

where k3 is a parameter like k1. k4 is a parameter concluding information on water-use efficiency. k5 quantifies of the non-linear effect of VPD on k4 [*Lin et al.*, 2018]. In this work, VPD is calculated from air temperature and relative humidity of air.

2.3 Conductance Model

Though the linear SIF-GPP relationship (Eqn 3) looks simple, the mechanism of the parameter LUE in is complex. Φ_f and Ω_c are relatively stable value [*Guanter et al.*, 2014; *Tol et al.*, 2014], and LUE is often calculated by reducing potential LUE using several environmental factors, such as temperature, soil moisture [*Yuan et al.*, 2007]. Previous work had also reported the hyperbolic relationship between SIF and GPP [*Damm et al.*, 2015; *Zhang et al.*, 2020]. Therefore, the relationship between SIF and GPP is far more complicated than linear. The link between SIF and GPP is because of the close relationship between SIF and electron transport rate (J) and J can be derived by SIF in [*Gu et al.*, 2019]:

$$\mathrm{J} = \mathrm{a\ q_L\ SIF} \tag{8}$$

Benefit from the carbon-pump mechanism, the GPP of C4 plants is linearly related to. For C4 plants[*Collatz et al.*, 1992], GPP can be derived by:

$$\mathrm{GPP_{gs}} = \mathrm{J}/4 = \frac{\mathrm{a\ q_L\ SIF}}{4\Omega_c} \tag{9}$$

a is an empirical factor supposed to be a constant under ideal environments, q_L is the fraction of open Photosynthesis II reaction centers, indicating the 'traffic jam' in the electron transport pathway from Photosystem II to Photosystem I. Note that, the Eqn 8 is designed for broadband SIF for PSII. In this paper, single NIR band SIF is used instead by assuming a linear relationship between single-band SIF and full band SIF. q_L ranges from 0-1 and decreases with increased PAR [*Baker*, 2008; *Gu et al.*, 2019]. In this paper, q_L is derived by:

$$q_L = \exp(-\beta \mathrm{PAR}) \quad (10)$$

β is a parameter denoting the sensitivity of q_L to the illumination. Due to data restrictions, Ω_c for the near-infrared band SIF was set as a constant in our study. gs for C4 plants is derived by inserting Eqn into the famous Ball-Berry model [*Ball et al.*, 1987]:

$$\mathrm{gs} = \mathrm{m}\,\frac{\mathrm{a}\, q_L\, \mathrm{SIF}}{4\Omega_c}\mathrm{Rh}/C_a + g_0 \quad (11)$$

where m is an empirical slope parameter, which is often treated as a constant for a specific ecosystem [*Miner et al.*, 2017]. C_a is the ambient carbon dioxide concentration and g_0 is the minimum conductance which is set as 0. Lack of an efficient mechanism gathering CO_2 from the air, C3 plants much more rely on the stomata to absorb CO_2 for the Calvin cycle. For C3 plants, the relationship between SIF and GPP is also affected by the dark reactions. The relationship between GPP and SIF for C3 can be expressed by [*Gu et al.*, 2019]:

$$\mathrm{GPP}_{gs} = \mathrm{a}\frac{C_i - \Gamma^*}{4C_i + 8\Gamma^*} q_L\, \mathrm{SIF}\frac{1}{\Omega_c} \quad (12)$$

C_i is the intercellular CO_2 concentration. Γ^* is the CO_2 compensation point in the absence of mitochondrial respiration, which can be set as a constant for specific plant type or calculated by air temperature [*Katul et al.*, 2010]. C_i can be eliminated by combining Eqn 12 with Fick's law $\mathrm{GPP} = \mathrm{gs} \times (C_i - C_a)$, then we have:

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$$\mathrm{GPP_{gs}} = \mathrm{a}\frac{\mathrm{GPP/gs} + \mathrm{C_a} - \Gamma^*}{4(\mathrm{GPP/gs} + \mathrm{C_a}) + 8\Gamma^*}\mathrm{q_L}\ \mathrm{SIF}\frac{1}{\Omega_\mathrm{c}} \tag{13}$$

gs and GPP_{gs} can be solved under the constraining of the optimality theory of stomatal behavior. [*Cowan and GD*, 1977; *Katul et al.*, 2010; *Way et al.*, 2014]. According to this theory, plants tend to adapt stomata to minimize the cost of water while maximizing carbon assimilation:

$$\mathrm{f(gs)} = \mathrm{GPP} - \lambda\,\mathrm{ET} \approx\ \mathrm{GPP} - 1.6\lambda\,\mathrm{gs}\,\mathrm{VPD/P} \tag{14}$$

$$\delta\mathrm{f(gs)}/\delta(\mathrm{gs}) = 0 \tag{15}$$

λ represents the marginal water cost of carbon assimilation. P is the air pressure. If we incorporate Eqn 13, 14, and 15, gs can be expressed as the function $\boldsymbol{\mathcal{F}}$ of SIF, q_L, λ, Γ, VPD and C_a:

$$\mathrm{gs} = \boldsymbol{\mathcal{F}}(\mathrm{SIF}, \mathrm{q_L}, \lambda, \Gamma, \mathrm{VPD}, \mathrm{C_a})$$

$$= -\frac{\mathrm{a\ SIF\ q_L}(4\Gamma - \mathrm{C_a})}{4(2\Gamma + \mathrm{C_a})^2} + \frac{\mathrm{a\ SIF\ q_L}(2\Gamma + \mathrm{C_a} - 3.2\lambda\,\mathrm{VPD})\sqrt{3.2\lambda\,\mathrm{VPD}\,\Gamma(\mathrm{C_a} - \Gamma)(2\Gamma + \mathrm{C_a} - 1.6\mathrm{VPD}\lambda)}}{6.4\lambda\,\mathrm{VPD}(2\Gamma + \mathrm{C_a})^2(2\Gamma + \mathrm{C_a} - 1.6\lambda\,\mathrm{VPD})} \tag{16}$$

Finally, with SIF-based gs, T can be calculated by the two-source Penman-Monteith method [*Leuning et al.*, 2008]:

$$\mathrm{Ac} = \mathrm{Rn} \times [1 - \exp(-0.5\mathrm{LAI})/\cos(\mathrm{SZA})] \tag{17}$$

$$\mathrm{T_{gs}} = \frac{\Delta\,\mathrm{Ac} + \rho\,\mathrm{C_p}\,\mathrm{VPD}\,\mathrm{ga}}{\Delta + \gamma\left(1 + \frac{\mathrm{ga}}{\mathrm{gs}}\right)} \tag{18}$$

Eqn 17 is the simple one-dimensional Beer's law model. Ac is the available energy of the canopy layer, Rn is net radiation, LAI is the leaf area index and SZA is the sun zenith angle. For Eqn 18, Δ is the rate of change of vapor pressure with temperature, γ is the psychrometric constant, C_p is the specific heat of air; ρ is the density of liquid water, and ga is aerodynamic conductance.

2.3 Model Calibration

Parameters of both the WUE model and the conductance model need to be calibrated (see Table 3). GPP and the water balance framework are used here to constrain the models. Total ET observed by eddy covariance measurement is composed of plant transpiration (T) and soil evaporation (LEs):

$$\mathrm{LE} = \mathrm{T} + \mathrm{LEs} \tag{19}$$

LEs can be calculated by soil available energy (see Table 2).Considering the nonlinearity and complicity of the models, the shuffled complex evolution (SUE-UA) algorithm [*Duan et al.*, 1994] is employed to fit parameters by maximizing the cost function G:

$$\mathrm{G} = 0.4\mathrm{NSE}(\mathrm{GPP_{ob}}, \mathrm{GPP_{model}}) + 0.6\mathrm{NSE}(\mathrm{LE_{ob}}, \mathrm{LE_{model}}) \tag{20}$$

where NSE is the Nash-Sutcliffe efficiency coefficient. The subscript $_{ob}$ means observed values and variables with a subscript $_{model}$ mean values are derived by models described above. All model estimations and statistical analyses were performed with Python 3.8.3 [*Harris et al.*, 2020; *Herman and Usher*, 2017; *Houska et al.*, 2015]. The description and calculation of all variables mentioned above are listed in Table 2.

3 Results

3.1 Performance of SIF- T model

Scatter plots between reference T_{Zhou} and T modeled by SIF are shown in Figure 1 (upper row). In general, both the WUE method and the conductance method improve the ability of SIF in modeling T. Compared with simple linear regression with R^2 = 0.51 and RMSE = 78.05 W/m^2, the WUE model has 10% higher R^2 = 0.56 and 2% lower RMSE = 76.24 W/m^2, while the conductance model has 39% higher R^2 = 0.71 and 30% lower RMSE = 54.50 W/m^2. The linear model and the WUE model tend to overestimate T at the high values area, while most points of T_{gs} fall near the 1:1 line.

The reference T_{Zhou} may have considerable uncertainty. Plants do not always keep a specific response (square root) to VPD like described in Zhou's method. Moreover, in some ecosystems, the soil evaporation can not be ignored even in the peak growing season [*Li et al.*, 2019; *Stoy et al.*, 2019]. Here we also compared the LE derived by three SIF-T models with LE observed by eddy covariance in Fig1 (lower row). The linear model, WUE model and conductance model have R^2 = 0.56, 0.61 and 0.73 and RMSE = 94.60, 91.20 and 68.07 W/m^2 respectively. Same as compared with T_{Zhou}, the conductance model outperforms the other two models with the highest coefficients of determination and the lowest RMSE. The WUE model also has better performance than the widely used linear model.

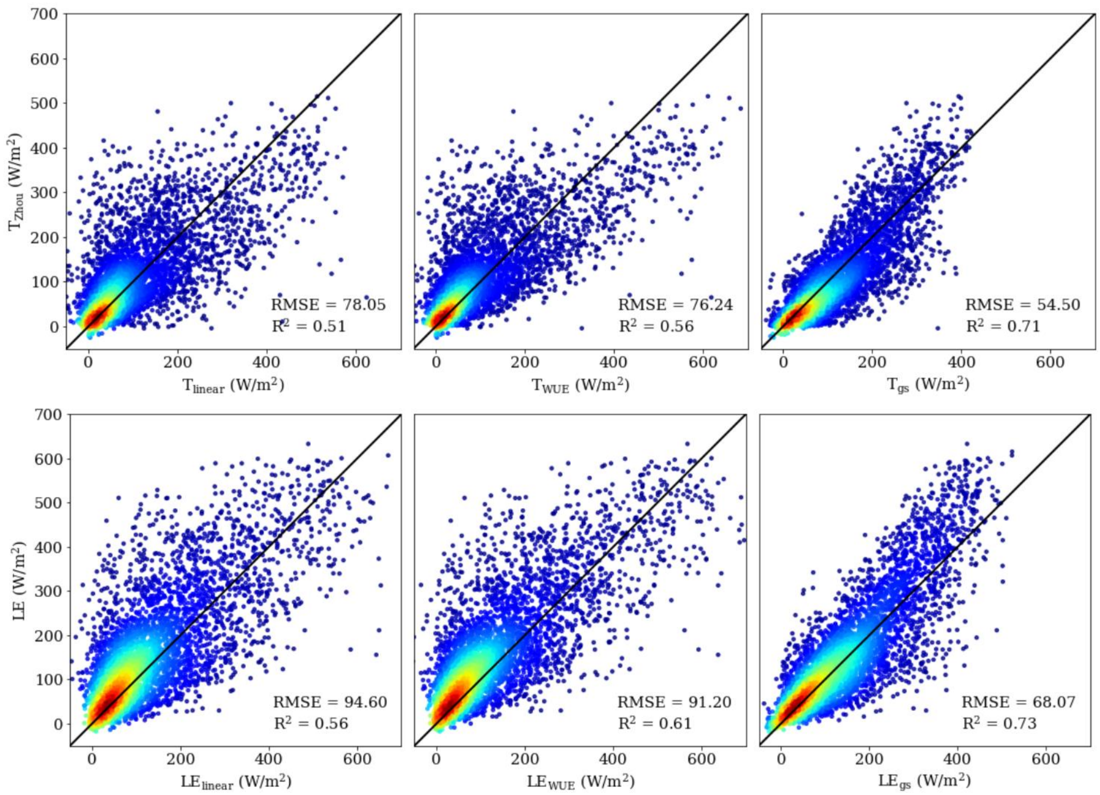
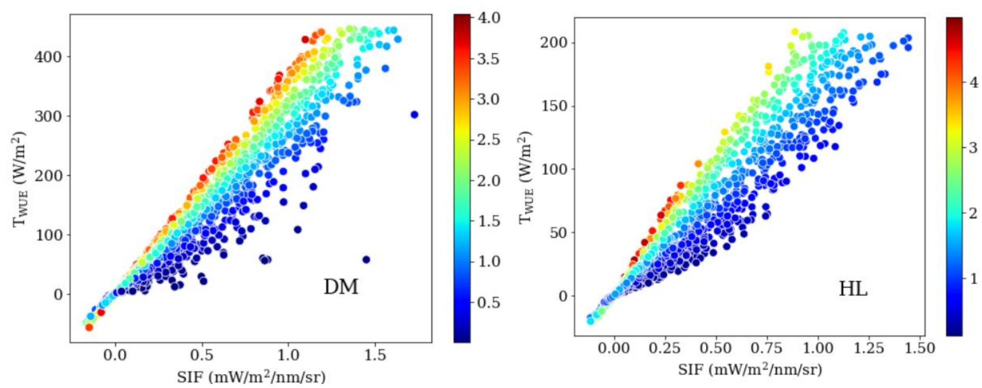


Figure 1. Relationship of T modeled by SIF and reference latent heat (Hourly). Colors indicate the density of points (from sparse to dense: blue to red). R^2 denotes the coefficient of determination. The unit of root-mean-square deviation (RMSE) is W/m^2. Black line denotes 1:1 line.

The performance of three models at different sites is shown in Table 4. When compared to T_{Zhou}, the conductance model shows the best performance at DM and HF sites with much higher R^2 = 0.84, 0.62, and lower RMSE = 47.98, 77.43 W/m^2 respectively. The linear model shows the best performance with R^2 = 0.58 and RMSE = 50.94 W/m^2 at the HL site. The WUE model outperforms other models at the NR site. When compared to LE observed by eddy covariance, the conductance model shows outstanding performance at all four sites. Besides, the WUE model has the lowest RMSE = 67.38 W/m^2 at the NR site.

3.2 Sensitivity analysis of variables in two models

To explore what influences the relationship between SIF and T, we analyzed the sensitivity of variables in WUE and conductance models. For the WUE model, the scatterplot between SIF and T_{WUE} is shown in Figure 2. T is the product of SIF and VPD in the WUE model, which means SIF and VPD interact with each other closely and the effect of the SIF is modified by the VPD. The parameter k5 for four sites are 0.33, 0.45, 0.97, and 0.02 respectively. With the increase of VPD, the slopes of SIF-T get steeper and points get denser, while in the low VPD condition, the points are relatively sparse, which indicates the relationship between SIF and T is more linear under high VPD. Especially we find the relation between SIF and T at the HF site is not sensitive to the VPD.



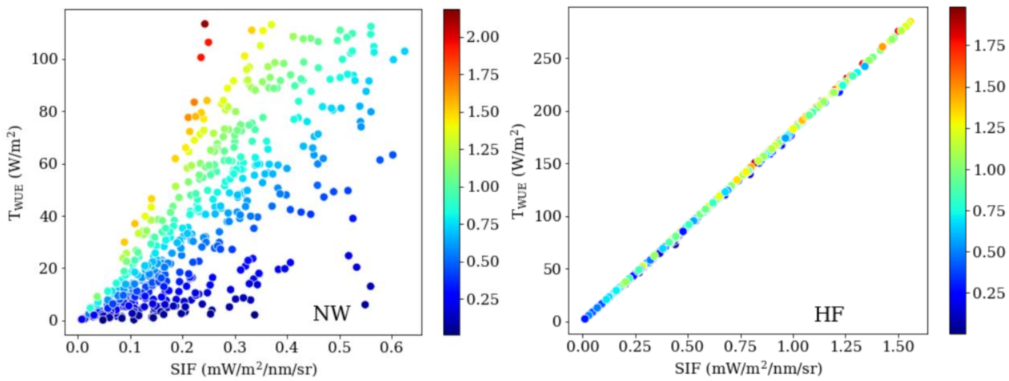


Figure 2. Scatter plot between SIF and T modeled by the WUE method. The vapor pressure deficit (VPD) has the unit kPa.

Atmospheric dryness is also important in modeling the stomatal behavior by SIF. For C4 plants, relative humidity is used to describe the response of stomatal conductance to air dryness in the empirical Ball Berry model. For C3 plants, we investigated the sensitivities of different variables in the gs model $\mathcal{F}$ by RBD-FAST-Random Balance Designs Fourier Amplitude Sensitivity Test [*Tarantola et al.*, 2006]. According to Figure 3, $\mathcal{F}$ is sensitive to VPD, λ, SIF, and q_L. VPD exhibits the highest first-order sensitivities with values equaling 0.09, which is much higher than SIF with value 0.05. The marginal water use efficiency λ also plays an important role in $\mathcal{F}$ with sensitivity value equaling 0.07. The fraction of open Photosynthesis II reaction centers q_L is as important as SIF (1^{st}-order sensitivity: 0.04), which is due to the electron transport rate J is the product of SIF and q_L (Eqn 4). What's more, the gs model is not sensitive to air temperature and ambient carbon dioxide concentration. However, VPD used here is calculated by temperature and relative humidity of the air. The temperature information contained in VPD (R^2 of Ta-VPD is 0.48) may impair the role of air temperature in the model. In this paper, q_L is calculated by a simple empirical equation of PAR. In fact, q_L is also related to the dark reaction but poorly studied [*Baker*, 2008; *Gu et al.*, 2019]. More researches about q_L will improve our understanding of the relationship between SIF and J, further the SIF-GPP and SIF-T relationships.

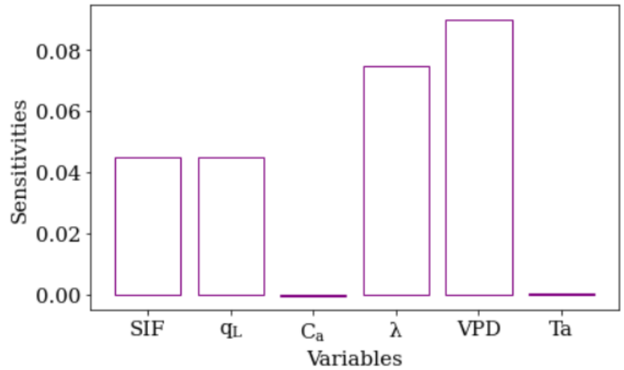


Figure 3. Sensitivity analysis of variables in the stomatal conductance model $\mathcal{F}$ of C3 plants. The height of bars shows the 1st order sensitivities of different variables.

4 Discussion

Above all, the assumptions of carbon-water coupling may affect our results. Compared with the linear model, though the influence of VPD on water-use efficiency is included in the WUE model, soil moisture, hydraulic conductance, and other environmental variables can influence water-use efficiency independently [*Leakey et al.*, 2019; *Lin et al.*, 2015; *Liu et al.*, 2020]. For the conductance model, plants under stress or competition tend to change the optimal stomatal conductance behavior [*Wolf et al.*, 2016]. The carbon-water economy is also influenced by traits of plants and environmental variables [*Bloom et al.*, 1985; *Buckley et al.*, 2017]. This concept is out of the scope of this paper, but a more physiologically based water-carbon coupling framework will improve the models from the bottom up.

Due to the absence of direct measurements of transpiration during the research period, three models were calibrated by the water budget balance framework, which might introduce uncertainty to parameters, further the performance of the models. Net radiation is separated into energy intercepted by canopy and soil available energy by 1D Beer's law. The simple structure of Beer's law can introduce great uncertainty, especially for heterogeneity canopy and plants with leaves highly anisotropic leaves in the azimuthal direction [*Ponce De León and Bailey*, 2019]. In the conductance model, canopy available energy is also used to estimate transpiration in the two-source Penman-Monteith model. So, the conductance model is more sensitive to the partition of energy, in other words, suffers more uncertainty from Beer's law. Uncertainty of input data might also affect our results. Firstly, VPD in the air was used to assess the aridity stress by assuming the canopy and the atmosphere are fully coupled. Yet, ecosystems (DM, HL, and HF) with dense closed canopy tend to decouple from the air [*De Kauwe et al.*, 2017; *Li et al.*, 2019; *Lin et al.*, 2018]. As both the WUE model and conductance model shows great sensitivity to VPD, using VPD at the leaf scale could help to improve the performance of the SIF-T relationship. Secondly, SIF data from four sites are measured by different instruments and derived by different methods as mentioned above. Moreover, the FOV and heights of the observation systems vary among sites. The emerge of remotely sensed SIF will fill the gap of the difference in the observation data. Last but not the least, the canopy-scale SIF was directly used to model transpiration due to data restriction. Nevertheless, recent papers indicated the relationship between SIF and GPP is strongly affected by the structure of the canopy [*Liu et al.*, 2019; *Zeng et al.*, 2019]. We suggest downscaling of SIF from the canopy scale to the photosystem scale may improve the performance of the model.

Data from four sites were used to test the performance of the models. It is inadequate to show the real potential of two models. With more and more in-situ observations from different ecosystems, understanding of the underlying mechanism between SIF and T will be deepened. Recently, SIF products with higher temporal-spatial resolution from different satellites, different bands [*Du et al.*, 2018; *Köhler et al.*, 2018; *Köhler et al.*, 2020], and derivative products based on machine learning [*Li and Xiao*, 2019; *Ma et al.*, 2020; *Yu et al.*, 2019; *Zhang et al.*, 2018] became available. WUE model and conductance model can be easily combined with remote sensing ET/T model like TSEB [*Norman et al.*, 1995; *Song et al.*, 2016] and PML ([*Zhang et al.*, 2019] or used for assimilating SIF into a land surface model. With these data and models in this paper, estimating T via SIF at the big scale becomes promising.

5 Conclusion

In this study, in-situ hourly SIF and corresponding meteorological variables, eddy covariance observation and vegetation indexes at C3 and C4 sites were collected. Two SIF-T models based on water-use efficiency and stomatal conductance were developed and tested upon this data. Both models outperformed simple linear analysis. The WUE model has 10% higher R^2 and 2% lower RMSE, while the conductance model has the 39% higher R^2 and 30% lower RMSE. Our results indicate the SIF-T relationship depends on air dryness. These two carbon-water coupling models can be easily combined with state-of-the-art remote sensing models or land process models. Moreover, with the emergency of high temporal-spatial resolution SIF data, SIF will not only be a powerful proxy for carbon flux but also water flux at the planetary scale.

Table 1. Summary of the stations used to build models.

	Latitude	Longitude	Period	Land Cover	Reference
DM	100.37°E	38.85°N	2017.6 – 2017.9; 2018.6 – 2018.9	Maize (C4)	[*Liu et al.*, 2018; *Liu et al.*, 2019]
HL	115.78°E	40.33°N	2017.7 – 2017.10; 2018.7 – 2018.10	Maize (C4)	[*Liu et al.*, 2013; *Liu et al.*, 2019]
NR	105.55°W	40.03°N	2017.6-2017.9; 2018.6-2018.7	Mixed temperate forest (C3)	[*Burns et al.*, 2015; *Magney et al.*, 2019]
HF	72.17° W	42.54°N	2013.6-2013.11	Evergreen needle leaf forest(C3)	[*Munger W*, 2020; *Yang et al.*, 2015]

Table 2. Input and intermediate variables. AWS denotes auto weather station. FAO indicates the computation methods of the variable is from http://www.fao.org.

Variables	Unit	Description	Source	Remarks
C_a	μmol/mol	ambient CO2 concentration	Observation	Eddy covariance
C_p	J/Kg/K	specific heat of air	1013	FAO

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LEs	W/m^2	Soil evaporation	$\frac{f\Delta(Rn - A_c)}{\Delta + \gamma}$	[*Fisher et al.*, 2008]
f	-	Soil evaporation constraint	$SM/(SM_{max} - SM_{min})$	-
ga	m/s	Aerodynamic conductance	$\frac{1}{v/(u*)^2 + 6.2(u*)^{-2/3}}$	[*Monteith and Unsworth*, 2013]
GPP_{ob}	$\mu mol/m^2/s$	Gross primary production	Separated from NEE observed by eddy covariance	[*Lasslop et al.*, 2010; *Reichstein et al.*, 2005]
LE	W/m^2	Latent heat	Observation	Eddy covariance
PAR	W/m^2	photosynthetically active radiation	Observation	AWS
P	kPa	Air Pressure	Observation	AWS
q_L	-	Fraction of open Photosynthesis II reaction centers	$\exp(-\beta\ PAR)$	This paper
Rh	-	Relative humidity	Observation	AWS
Rn	W/m^2	Net radiation	Observation	AWS
SIF	$mW/m^2/sr/nm$	Sun-induced chlorophyll fluorescence	Observation	-
SM	%	Soil moisture	Observation	Thermal Dissipation Probe
Ta	°C	Air temperature	Observation	AWS
u^*	m/s	Friction Velocity	Observation	Eddy covariance
v	m/s	Wind speed	Observation	AWS
VPD	kPa	Vapor pressure deficit	$(100 - Rh)/100 \times 0.6108 \times \exp(17.27\ Ta/(Ta + 237.3))$	FAO
Δ	kPa/K	Slope of saturation vapor pressure curve	$(2503 \exp(17.27\ Ta/(Ta + 237.3)))/((Ta + 237.3)^2)$	FAO
γ	kPa/K	psychrometric constant	$0.665 \times 0.001P$	FAO
Γ	μmol/mol	CO2 compensation point in the absence of mitochondrial	$36.9 + 1.18(Ta - 25) + 0.036(Ta - 25)^2$ for C3; 0 for C4	[*Katul et al.*, 2010]
ρ_a	kg/m^3	Air density	$1.292 - 0.00428\ Ta$	FAO

Table 3. Parameters needed to be calibrated.

	Parameter	Lower	Upper	Reference
Linear model	K1	5	50	[*Liu et al.*, 2017; *Sun et al.*, 2017]
	K2	3	50	[*Huang et al.*, 2016]
WUE model	K3	5	50	[*Liu et al.*, 2017; *Sun et al.*, 2017]
	K4	3	30	[*Zhou et al.*, 2015]; This paper
	K5	0	1	[*Lin et al.*, 2018]
Conductance model (C4)	β	0	0.001	This paper; [*Gu et al.*, 2019]
	a	10	300	This paper
	m	2.5	8.8	[*Miner et al.*, 2017]
Conductance model (C3)	β	0	0.01	This paper; [*Gu et al.*, 2019; *Katul et al.*, 2010]
	a	10	300	This paper
	λ	10	200	[*Cowan and GD*, 1977; *Katul et al.*, 2010]

Table 4. Coefficient of determination (R^2) and root mean square error (RMSE) at different sites. Best values are marked with the bold font.

	Reference	DM		HL		NR		HF	
		R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
T_{linear}		0.46	104.25	**0.58**	**50.94**	0.49	35.32	0.45	70.66
T_{WUE}	T_{Zhou}	0.55	99.11	0.55	53.66	**0.69**	**29.26**	0.45	71.80
T_{gs}		**0.84**	**47.98**	0.57	54.79	0.46	41.27	**0.62**	**77.43**
LE_{linear}		0.56	119.97	0.52	67.69	0.27	68.69	0.44	81.92
LE_{WUE}	LE	0.55	114.20	0.55	66.71	0.36	**67.38**	0.44	84.87
LE_{gs}		**0.87**	**69.36**	**0.60**	**64.53**	**0.40**	68.82	**0.55**	**70.71**

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